NBSIR 73-277

Evaluation of a Pressurized Stairwell Smoke Control System for a 12 Story Apartment Building

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U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary

NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

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by

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ABSTRACT

An NBS study to evaluate the effectiveness of a pressurized stairwell smoke control system in a high rise apartment building is summarized and discussed in the light of experimental results, analysis, and computer prediction. A quantitative experimental technique of smoke simulation and smoke movement measurement is described, supplemented by basic physical laws necessary for correlation with small fires, and illustrated by the results of an actual field experiment. Experiments were conducted in a 12 story apartment building constructed on the Operation BREAKTHROUGH prototype site in St. Louis, Missouri. The experimental results are then further extended to a wider range of ambient weather conditions by way of computer prediction calculations. General conclusions and relevant recommendations as a result of the study are also presented.

Key Words: Analysis; basic correlation formulas; computer calculations; high-rise building fire; Operation BREAKTHROUGH; pressurized stairwell; quantitative experiment; smoke control; smoke simulation

1.0 INTRODUCTION

The many fire safety problems introduced by smoke have been widely recognized. Traditionally, the characterization of smoke and smoke control in building fires has been very actively investigated by the fire research community. Of late the investigations have received new impetus due to a focus of attention on high rise building fires. Smoke as a critical factor in high rise building fire safety has been well discussed by a number of authors [1,2]. It is well known that the laws of nature dictate that hot smoke and gases from a fire will move upwards. In the case of fire in a conventional high rise building the combination of bouyancy force due to fire and the stack effect due to weather conditions can cause air and smoke to travel upwards in stairways, elevator shafts and vertical utility shafts. This vertical movement of smoke not only speeds smoke infiltration to the upper levels, it can also leave all the escape paths smoke logged. This smoke logging of stairway and elevator shafts presents the added hazard of obstructing fire fighting as well as preventing safe evacuation from a building fire.

Recent research abroad and in the United States has indicated the feasibility of smoke control by means of ventilation; and in particular maintaining the exitways smoke free by pressurization of the stairwells. From a brief survey of the current status of smoke control in high rise buildings it appears that the basic principle and guidelines for this technique of smoke control in high rise buildings have been developed [3-10]. For a more detailed literature discussion one is referred to Hobson and Stewart's article [11]. For general guide lines on high rise smoke control one is referred to Galbreath, McGuire and Tamura's article

on control of smoke movement [12].

Current smoke control activities at the NBS are aimed at putting the techniques to practice by providing a quantitative design base. With this in mind two approaches have been taken: One, to conduct high rise smoke simulation experiments that can quantitatively measure the smoke movement under pressurized and unpressurized conditions; and second, in conjunction with the first approach, to model the smoke simulation experiments analytically and to establish a smoke movement prediction computer program for optimum smoke control design and standards.

2.0 CONCEPTS OF SMOKE MOVEMENT DERIVED FROM BASIC PRINCIPLES

Following is a summary of useful concepts applicable to smoke movement study and control. The inclusion of certain concepts is guided by their usefulness in practical smoke control rather than their elegance, and to facilitate discussions on smoke simulation experiments in the following sections. An attempt will be made to illustrate these concepts by derivations from elementary principles. The purpose of these derivations is to present the concepts in simple expressions to make them available to a wider spectrum of interests in the fire community.

2.1 Movement of Air Containing Smoke

Fluid motion in general, including air or smoke, is caused by the action of natural and mechanical forces. In a fire the two motivation forces that cause smoke movements are buoyancy force and pressure forces.

Buoyancy forces in a fire are caused by density changes due to heating. The relative differences in density then sets up a convective flow in a

gravity field. Pressure forces can originate in a number of ways, e.g. by restriction of volume expansion, by stack effect or by the introduction of ventilation controls. Before discussing these forces, consider smoke motion caused by a generalized pressure force, p. The momentum equation for the flow field in this case can be simply written as,

$$\rho \overline{V} \nabla \overline{V} = -\nabla p \qquad (1)$$

where

ρ: the gas density,

$\overline{V}$: the gas velocity vector

p: the pressure distribution of the flow field

∇: the gradient operator.

Integrating (1) along the direction of smoke motion one obtains

$$1/2 \rho V^2 = |\Delta p| \qquad (2)$$

where

Δp: the pressure difference

Assume that gas density change is governed by the ideal gas law,

$$\rho = \frac{P}{RT} \qquad (3)$$

where

T: the absolute temperature

R: the gas constant

Combining (2) and (3) and evaluating for air under one atmosphere condition, with R equaling 53.3 ft.lb/lb_m °R one obtains

$$V = 174 \sqrt{\Delta p T} \qquad (4)$$

where

V: velocity in feet per minute

T: Temperature in degrees Rankine

Δp: Pressure difference in inches of H_2O

If Δp is expressed in lb/ft^2 we have

$$V = 104\sqrt{\Delta p T} \qquad (5)$$

Equations (4) and (5) clearly shows that it takes very little pressure difference to move air at a considerable velocity, e.g., 0.01 inch water pressure or 0.05 lb/ft^2 can generate velocity of 400 ft/min or 4.5 mph at room temperature.

2.2 Buoyancy Force

Consider the bulk ambient air temperature to be T_o and the corresponding density ρ_o. The buoyancy force F_B per unit volume due to locally heated air at temperature T and density ρ in the gravity field is simply,

$$F_B = (\rho_o - \rho)g \qquad (6)$$

Substituting (3) in (6) at constant pressure, one obtains,

$$F_B = \frac{pg}{R}\left(\frac{1}{T_o} - \frac{1}{T}\right)$$

Evaluating for air at one atmosphere pressure we have,

$$F_B = 40\left(\frac{1}{T_o} - \frac{1}{T}\right) \qquad (7)$$

where

F_B is in lb/ft^3

Transforming to pressure difference for a given flame height H, we have

$$\Delta P_B = 7.7\left(\frac{1}{T_o} - \frac{1}{T}\right) H \qquad (8)$$

where

Δp_B: pressure difference due to buoyancy force in inches H_2O

H: flame or hot gas column height in feet

The above formula shows that for a fully developed fire with gas temperature reaching 1600°F and confined to one floor with a ceiling height of 10 ft the pressure difference due to buoyancy can reach 0.1 inch H_2O.

2.3 Estimate of Volume Outflow From a Fire

Consider the following simplified cellulose burning reaction in air as representing one possible form of wood burning in a fire,

$$C_6H_{10}O_5 + 6\ O_2 + 24\ N_2 \longrightarrow 6\ CO_2 + 5\ H_2O + 24\ N_2 \qquad (9)$$

The above reaction indicates that for every lb-mole of cellulose 30 lb-moles of air are required to sustain burning, resulting in 35 moles of total combustion products. Knowing that one lb-mole of cellulose weighs 162 lbs and one lb-mole of any gas occupies 359 ft^3 at STP, one can calculate the volume of combustion products per pound of cellulose consumed as follows,

$$\mathcal{V} = \frac{359}{162} \times 35\ ft^3 = 77.5\ ft^3 \text{ at STP} \qquad (10)$$

Thus for a given burning rate R lb/min of cellulose and a burn room average air temperature T we have

$$\mathcal{V} = 77.5\ \overset{\circ}{R}\ \frac{T}{T_o} \qquad (10a)$$

We see that in a fire where temperature can reach as high as 1600 $^\circ$F the effect of temperature increase can represent a five fold expansion of gas at room temperature.

The stoichiometric reaction stated in equation 9 also indicates an air to cellulose ratio of 5.3 to 1 by weight. This checks with Thomas' calculation [13] that in a ventilation controlled fire the air to fuel ratio can be estimated to be in the range of 5.45 to 1 by weight. It may be pointed out that the roughly 5 to 1 to fuel ratio fire is a lower

limit estimate. More typical ratios of air to fuel appears to be approximately 10 to 1 according to actual measurements of hot gaseous flow from a fire in Ref. [14]. An upper limit of hot gaseous flow from a fire appears to be 20 to 1 according to experimental measurements in Ref. [15]. Thus the estimate of hot gaseous flow per pound of burned cellulose given in equation (10) is a conservative extimate. In a more typical fire the amount of outflow can be doubled. In general we can write,

$$77.5\ \mathring{R}\,\frac{T}{T_o} \le \forall \le 310\mathring{R}\,\frac{T}{T_o} \qquad (10b)$$

2.4 Pressure Force Due to Volume Outflow From a Fire

The hot gases generated by a room fire will expand according to ideal gas law and be pushed out of the room through openings. In so doing the gas will exchange heat for kinetic energy. In a fire situation where the absolute pressure remains near one atmosphere the velocity of the hot gases can be estimated from the burning rate and the size of the room openings to the outside.

In section 2.3 we have estimated that for ventilation controlled fire the volume of gaseous product per pound of burning cellulose is 77.5 ft^3 at STP. Let $\mathring{R}$ be the burning rate in pound per minute, then

$$V = \mathring{R} \times 77.5 \times \frac{T}{T_o A} \qquad (11)$$

where

V: the average flow velocity in fpm through openings

T: the burn room temperature

T_o: the ambient room temperature

A: area of openings in ft^2

The pressure due to this flow rate can then be obtained from equation (4) or (5).

Substituting (11) in equation (4) and solving for Δp, we obtain the pressure force due to this volume outflow given by,

$$\Delta p = 2.0 \times 10^{-1} \left(\frac{\overset{\circ}{R}}{T_o A}\right)^2 T \text{ for stochiometric burning}$$

where

Δp: pressure difference in inch H_2O

T_o, T: temperature in degree Rankine

$\overset{\circ}{R}$: burning rate in lb/min

In general for varying degree of air supply to a fire as discussed in section 2.3, we have

$$2.0 \times 10^{-1} \left(\frac{\overset{\circ}{R}}{T_o A}\right)^2 T \leq \Delta p \leq 8.0 \times 10^{-1} \left(\frac{\overset{\circ}{R}}{T_o A}\right)^2 T \qquad (12)$$

The above formula shows that the pressure difference across the outlet of a burn room is directly proportional to the square of burning rate, and inversely proportional to the square of the burn room outflow area. For example in a fully developed room fire with a burning rate of 10 lb/min and 1600°F gas temperature, a 20 ft^2 doorway opening can induce a pressure difference of .0004 to .002 in H_2O, whereas a 2 ft^2 small window opening can induce a pressure difference of .04 to 0.2 inch H_2O across the window opening.

2.5 Pressure Force Due to Stack Effect

The well known stack effect in a high rise building is caused by the difference in hydrostatic pressure due to two air columns at different temperatures. Thus the pressure difference is given by

$$\Delta p \ (\rho_o - \rho) \ gh$$

where

ρ_o: the outside density

ρ: the inside density

g: the gravity constant

h: distance from neutral plane

Assuming the ideal gas low are given in equation (3) we have

$$\Delta p = \frac{pg}{R} \left(\frac{1}{T_o} - \frac{1}{T}\right) h$$

Considering one atmosphere condition, we can express the above as

$$\Delta p = 7.7 \left(\frac{1}{T_o} - \frac{1}{T}\right) h \qquad (13)$$

where

h: is in ft

T: in degrees Rankine

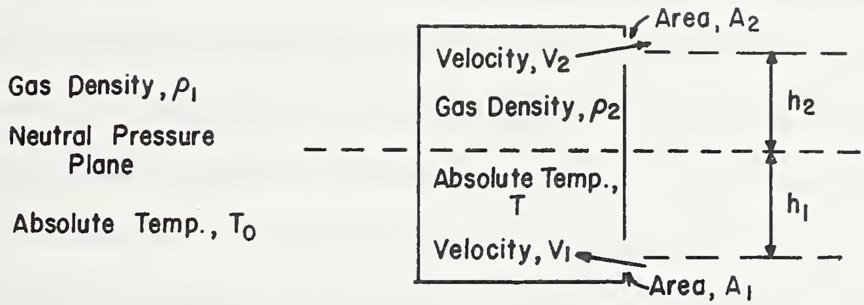
Δp: in inches of water

The above formula indicates that for a 100 ft tall building with neutral plane at mid height and a 70°F temperature differential, a maximum of 0.1 inch H_2O pressure difference can be induced by stack effect.

2.6 Determination of Location of Neutral Plane

To calculate the pressure force due to stack effect in formula 13 one needs to determine the location of neutral plane. The stack effect causes a circulatory motion with a transition neutral plane. The stack effect causes a circulatory equilibrium pressure. This neutral plane location can be easily determined by invoking the law of conservation of mass.

Consider the simple case of a building with only top and bottom openings.



With variables indicated as in above sketch, by conservation of mass, we have,

$$\rho_1 A_1 V_1 = \rho_2 A_2 V_2 \tag{14}$$

From equation 4 and equation 13 we obtain

$$V_1 \sim \sqrt{h_1 T_o} \quad \text{and}$$

$$V_2 \sim \sqrt{h_2 T} \tag{15}$$

Combining (14), (15) and solve for the ratio h_2/h_1, and assuming $\rho_2/\rho_1 \sim 1$ from small temperature difference, during each fire we have,

$$\frac{h_2}{h_1} = \frac{A_1^2 T}{A_2^2 T_o} \tag{16}$$

This is a formula for determining the location of neutral plane when given size of top and bottom openings, and inside and outside temperatures.

3.0 Discussion of Smoke Simulation and Smoke Control

In terms of smoke simulation and smoke control results of the previous section can be summarized as follows:

1. To simulate a room fire in terms of gaseous outflow two additional factors need to be considered besides heat. They are the volume outflow and pressure difference created by a room fire. We have shown that the rate of volume outflow can be simply related to the burning rate as

indicated in equation 10 and the pressure difference due to this overflow is proportional to the square of the burning rate. Furthermore in a room fire with the burn room door open as discussed in section 2.4 the pressure difference created by the outflow from the burn room is on the order of .01 in H_2O or less. Thus the simulation of smoke movement during early stages of a fire by warm rather than hot smoke is relatively simple and can now be related to a real fire in terms of volume flow and pressure difference.

2. The pressure created by a buoyancy force due to the presence of a layer of hot gases is proportional to the thickness of the layer. Thus the effect of buoyancy force only makes itself felt when the vertical height of the fire becomes extensive. From equation 8, a hot gaseous layer 1 ft thick with an average gas temperature of 1600°F only sustains a pressure of .01 in H_2O across it. In other words in terms of smoke control in high rise buildings the buoyancy force created by the fire itself is not the critical factor until the building is extensively involved in fire. However, if two stories are fully involved in fire with a temperature of 1600°F the pressure difference due to buoyancy can be as high as .2 inch H_2O according to equation 8.

3. The pressure created by stack effect on the other hand is proportional to the height of the building. Thus in a high rise building when there is a significant temperature difference inside and outside due to weather, the stack effect is the major factor in smoke control even at the early stages of a fire, e.g. from equation 13, a 10 story building in the winter with a 100°F temperature difference, can produce pressure difference of .16 in H_2O. The present design philosophy using pressurized

stairwells following the Canadian example [12] is aimed at countering the pressure difference and volume flow rate induced by the stack effect. This calls for rather large flow rates during evacuation. However, it has seldom been mentioned that the stack effect in a stairwell can be reduced by the operation of the pressurization system. Since the pressurization system circulates outside air into the stairwell, the stairwell temperature can quickly reach equilibrium with the outside and thus reduce the stack effect. This actually inhibits the upward movement of the smoke in the stairwell. According to these considerations it appears to be more relevant to design pressurization to aim at countering the buoyancy force due to a fire. Since, the stack effect is a function of the indoor and outdoor temperature difference it is subject to weather variations, this is considered in Section 7.0 by means of computer simulation.

4.0 HUD OPERATION BREAKTHROUGH SMOKEPROOF STAIRWELL REQUIREMENT

4.1 Operation BREAKTHROUGH Criteria

Criteria L.4.2.9, Volume I, Operation BREAKTHROUGH Guide Criteria recommended that one exit stairway in apartment buildings over six stories in height be a smokeproof enclosure. The definition of smokeproof enclosure was:

> "A smokeproof stair enclosure is a stair enclosure so designed that the movement of products of combustion, produced by a fire occurring in any part of the building, into the smokeproof stair enclosure, should be limited by the use of an appropriate design method to ensure that with the minimum winter exterior dry bulb temperature

(based on the ASHRAE design tables for 97-1/2 percent probability for the geographical location of the building), the atmosphere in the stair enclosure should not, during a period of two hours, develop a contaminated atmosphere emanating from the fire area that is more than one (1) percent of the volume of the smokeproof stair enclosure."

Each Housing System Producer was given the choice of using any design method he wished in meeting the criteria noted above. For guidance, one of the three methods described in the National Research Council of Canada's publication, "Explanatory Paper on Control of Smoke Movement in High Buildings" [12] was suggested.

4.2 Method Chosen

For their MFHR at St. Louis, the Housing System Producer (HSP) elected to use a modification of NRC Method III, "Pressurized Vertical Shafts." In this method the following conditions apply:

1. The stair enclosure chosen to be the smokeproof enclosure shall have equipment capable of providing a mechanical air supply into the shaft at the upper end of not less than 15,000 cfm plus

a. 100 cfm for each door (having a perimeter of not more than 20 feet) that is equipped with a tight-fitting weatherstripping or,

b. 200 cfm for every other door (having a perimeter of not more than 20 feet) into the stairshaft.

2. Each stairshaft shall have a vent at street level, opening either directly outside or into a vestibule or corridor that has a similar opening to outside, having an opening of not less than 0.5 square feet for every door that opens into the stairshaft, other than doors at street floor level, but in any case not less than 20 square feet.

3. The vent at the bottom of the stairshaft may be provided with a window, shutter or door, which shall open automatically, unless there is a central control facility from which the window, shutter or door may be opened manually, and shall be designed to remain in the open position during the fire emergency.

4. Manual or automatic operation of a fire alarm box on any floor shall initiate the mechanical air supply to the smokeproof stair enclosure as provided in (1) above and shall cause the window, shutter, or door to open as provided in (3) above.

4.3 Special Conditions

For the 12-story building at St. Louis, the basic air supply to the smokeproof stair enclosure was set at 10,000 cfm instead of the 15,000 cfm stipulated above. Also, the HSP elected to use weatherstripped doors on the smokeproof stair enclosure thereby reducing additional air supply needed for door leakage from 200 cfm to 100 cfm per door. As a result, the total air supply provided by the HSP was approximately 11,200 cfm, made up of 10,000 cfm plus 1,200 cfm for door leakage.

The air supply fan for the smokeproof stair enclosure was placed on the roof over the stairtower. Both this fan and the automatic-opening device on the grade-level door to the outside were connected to the building fire alarm system. Operation of the building fire alarm system

starts the fan and opens the grade-level exit door.

5.0 EXPERIMENTAL PROGRAM

An experimental program to study the effectiveness of smoke control in a stairwell by pressurization was conducted from March 23 to 28, 1973, at a twelve story apartment building constructed under Operation BREAKTHROUGH at St. Louis, Mo. The experiment was designed to study systematically the effect of various key variables on smoke movement in a high rise building. Smoke was simulated by a net air flow of 1800 CFM from a room designated as the burn room. The air was mixed with a predetermined percentage of SF_6 tracer gas* and heated to a temperature 10 degrees above the corridor temperature. The range of reference concentrations of the SF_6 tracer gas** in the air from the burn room contains from 0.3 to 10 parts per million, which is the maximum reference concentration from each experiment. Altogether ten simulations were tested. Table 1 lists the description of the tested configurations. Key variables investigated include simulated fire on the second and ninth floors, with and without stairwell pressurization, and a number of stairwell door openings. The stairwell was pressurized by a blower delivering 11,000 CFM. This flow rate resulted in a high velocity flow and high noise level in the stairwell. Figs. 1 and 2 show the floor plans of the second and ninth floors respectively of the 12th story building. Rooms used to

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*SF_6 was chosen as a tracer gas because of its electron capture property for detection, as well as being odorless, colorless, harmless and stable.

**OSHA concentration limits of SF_6 is 1000 PPM as set forth in the Federal Register, Volume 36, No. 157, August 13, 1971.

simulate the burn room are indicated in the Figures. Fig. 3 shows the location of the air supply louver at the top of the stairwell and the vent (door) opening at the bottom of the stairwell. This door had to be opened manually as the automatic door release was inoperative.

5.1 Experimental Procedure

Prior to the beginning of each experiment the burn room air was preheated to a temperature of 80°F by setting of the thermostat of the forced air heating furnace in that apartment. Air was directed from the outdoors into the furnace inlet by means of a cardboard duct. A window box-type fan as shown in Figs. 1 and 2 was used to draw the preheated air from the burn room and blow it into the corridor. A cardboard mask was installed at the hall on the same vertical plane as the fan to allow air from the burn room to be channeled through the fan only. The measured air flow through the fan was approximately 1800 CFM with an average pressure of .04 in. H_2O across the fan.

At time zero a lecture size bottle of SF_6 gas located in front of the fan was turned on to continuously deliver a predetermined amount of SF_6, to be mixed with the burn room air supply. The infiltration of SF_6 gas into the rest of the building was then traced by sampling at 4 designated floors at both the north stairwell and mid-corridor at 5-minute intervals. The floors chosen for measurement were the second, fifth, ninth, and eleventh. In the sampling routine, one man was stationed in the stairwell, and another in the building to collect integrated gas samples at the above chosen floors beginning at 5, 15 and 25 minutes after time zero. Each vertical traverse of the building from the 11th floor

to the second floor took approximately 4 minutes. The gas samples collected in ballons were then analyzed by a third man during and immediately after each test.

5.2 Instrumentation

5.2.1 Flow Rate Measurements

Flow rates were determined by average velocities. Velocity measurements were performed by using a thermo-anemometer with a low range 100 - 500 fpm and a high range of 500 - 1200 fpm. Average velocities were obtained by making a traverse of 9 points for square or rectangular ducts.

5.2.2 Pressure Measurements

Static pressures were measured by a Magnehelic pressure gauge of .01 to 1.0 in. H_2O range.

5.2.3 SF_6 Gas Metering

In tests 3a, 3b, 4b, 5a, 7 and 8 the continuous release of SF_6 gas was metered by a ball type flow meter with a range of 1 to 10 ft^3/hr. A slight turn of the needle valve with the ball barely off its seat results in burn room SF_6 concentrations varying from 3 to 10 ppm for different tests. Subsequent test experience showed that with this kind of burn room concentration it takes more than four hours of purge time before the building is cleared of SF_6 for the next test. In order to speed up the purge time between tests it was decided to run the rest of the tests at a lower burn room concentration. Since the dispersion of SF_6 is exponential, to cut down the dispersion time by half, one needs to drop the burn room concentration by an order of 1 ppm (1000 ppb) is quite

acceptable to our experimental requirement since the gas analyser sensitivity is readable at 1 ppb. This means that the relative concentration can be measured to one part in one thousand.

A rough estimate showed that in order to bring the air supply from the burn room fan to SF_6 concentration of 1000 ppb, a continuous release of 100 cc/min or 2 ft^3/hr of SF_6 is required. For tests 5c, 5g and repeat of 5a and 3e another ball type flow meter of the appropriate range was used. The flow meter was calibrated by the soap film displacement method over the measuring range.

One additional problem associated with SF_6 metering was the unsteadiness of the SF_6 flow for experiments 3b, 4b. Although the relative concentration was calculated by normalizing the sample concentration by the burn room concentration at the corresponding time, extreme unsteadiness can result in lack of reproducibility. The unsteady SF_6 metering was found to be caused by the first flow meter used. This flow meter was operated by barely lifting the ball from its seat. The situation was remedied by using another flow meter with a lower range operating in the neighborhood of 100 cc/min.

5.2.4 SF_6 Analysis

SF_6 samples were analysed by a portable gas chromatograph having an electron capture cell fitted with a 300 mc tritium source. The response of the instrument to SF_6 is exponential and the usable range is between 1 and 100 ppb. Dilution of samples when necessary was effected by a 10 to 1 critical orifice.

6.0 DISCUSSION OF EXPERIMENTAL RESULTS

In tables 2 to 11 the results of SF_6 analyses for 10 tests are summarized. SF_6 concentrations for each chosen floor at the specified time intervals are listed in ppb, and percentage concentration normalized by the "burn room" SF_6 concentration. Burn room gas samples were taken in the hall between the "burn room" and the corridor. Comparative evaluations of smoke concentration for the different test simulations are plotted on Figures 4 to 12:

1. Fig. 4 compares the corridor smoke concentrations at the 15 minutes for tests 3b and 4b. The result is that stairwell pressurization in this case not only kept smoke concentration in the stairwell below the 0.001 or undetectable level, it also reduced the smoke level in the building corridor significantly.

2. Fig. 5 shows smoke concentrations in the stairwell at 15 minutes. Note that in all tests with the pressurization on, the smoke level in the entire stairwell was either below 0.1% or undetectable whereas in case 4b with pressurization off the measured concentration at 15 minutes ranged from 4 to 70%.

3. Figs. 6 and 7 compare smoke concentration in the corridors for simulated fire on the second and ninth floor respectively for different stairwell door openings.

4. In Figs. 8 and 9 the stairwell pressurization "shake down" test results are presented for the case of simulated fire on the second floor and the ninth floor respectively. In each case the "shake down" procedure was to open one stairwell door at a time at two minute intervals and then measure the SF_6 concentration in the stairwell at that level. Every door

after being opened remained open for the rest of the test so that a cumulative effect of door openings was obtained. The routine started five minutes after initiating the SF_6 flow in the burn room, with sample collections proceeding from the 11th floor down to the second floor. Using a 1% concentration as a critical cut off limit, it appears that for a simulated fire on the second floor, the stairwell pressurization failed after opening the 5th floor stairwell door, and for a simulated fire on the ninth floor, failure occurred after the opening of the 9th floor stairwell door.

5. The force required to open stairwell doors during the pressurized mode was also measured, by means of a graduated spring scale, since the additional force due to pressurization can be a critical design consideration. The measured force and the calculated force from pressure measurements are plotted in Figure 10. The correlation between measured force and calculated force appears to be good except for the 11th floor stairwell door. The total force required to open the doors under pressurization conditions was below 30 pounds except the 11th floor door. For this door the measured force required is 42 pounds and the calculated force is 34 pounds.

7.0 STAIRWELL PRESSURE FOR EXTENDED WEATHER CONDITIONS

The experimental results obtained by the smoke simulation program confirmed the feasibility of stairwell smoke control by pressurization. The experiments were performed only under moderate 60°F outside weather conditions and the effect of more severe weather conditions should also be investigated. Since direct control of ambient conditions was not possible, an alternate indirect way to extend the investigation is through

computation and prediction. The computer program chosen for this purpose was a modified numerical program originally developed by Sander and Tamura [16]. This numerical program based on Ref. [14] calculates pressure differences in a high rise building by taking into account the buoyancy force, stack effect due to temperature difference, net flow due to the air handling system, and leakage flows by empirically estimated leakage characteristics through doors, walls, and floors.

With the leakage characteristics estimated according to Ref. [14], and treating the stairwell shaft as a building with large floor leakage and the building as a vertical shaft, as suggested by T. Kusuda of National Bureau of Standards, a series of computer calculations were performed to predict the pressures in the subject high rise apartment building.

The variables investigated included simulated smoke production on second and ninth floor levels, outside weather conditions with temperatures 15°F, 60°F, and 90°F, and different stairwell door openings. Calculated pressure differences across stairwell doors are presented in Figs. 11 and 12 along with the measured pressure differences. Fig. 11 presents calculations for the case where pressurization is on and all stairwell doors closed. For all cases calculated the building temperature is assumed to be 72°F. The pressure difference across the stairwell doors in each case is caused by the combined effects of the pressurization system and the temperature difference between the building and the stairwell. Agreement of calculation for the case of 60°F outside temperature with the corresponding case 3a experimental measurement is fair.

Fig. 12 presents calculations for the case where pressurization is on, and the second and 11th floor stairwell doors are open. Agreement of

the calculations for a 60°F outside temperature with the corresponding case 3e experimental measurement is excellent. In both Figs. 11 and 12 one can see that according to the computer calculations the stairwell pressure differences remained positive for the two building configurations studied for both extreme temperatures of 15°F and 90°F outside air. Positive stairwell pressure difference is the necessary condition for preventing smoke from entering the stairwell. Thus results of the computer calculation for extended temperature ranges indicate that for the more severe condition of a second floor fire, the stairwell has favorable pressure conditions to remain smoke free up to opening of the second and 11th floor stairwell doors, and at both 15°F and 90°F outside temperatures, assuming the stairwell reaches the ambient air temperature.

In relation to the computer calculations it may be relevant to point out that in the subject high rise apartment the pressurization unit circulates 11,000 CFM of outside air through the stairwell. Experimentally it was found that the stairwell air reached the temperature of the outside air in less than a minute. Computer prediction results may lead to different conclusions if the pressurization unit circulates conditioned air, thus requiring different stairwell temperature input to the computer program. However, in the subject high rise apartment the proper temperature input under pressurization was that of the ambient temperature level.

8.0 CONCLUSIONS AND RECOMMENDATIONS

Major conclusions as a result of the present study are:

1. Stairwell pressurization can be very effective in preventing smoke from entering stairwells even with several doors open. The effectiveness of the 11,000

cfm blower in this case was clearly illustrated by this study.

2. The simulation of smoke movement due to a fire in a high rise building by using SF_6 as tracer gas mixed with a warm air supply is feasible. The model can be related to a real fire in terms of volume outflow, heat energy output and average pressure difference across the burn-room doorway.

3. Present smoke control design guidelines are in need of optimization by using quantitative experiments and computer calculations.

Relevent future recommendations as a result of the present study are:

1. Smoke simulation experiments by using SF_6 as a tracer gas mixed with heated air should be relatable to a wide range of early burn-room fires through basic physical laws in terms of volume outflow, heat energy output and average pressure across the burn-room door. Basic formulas for this comparison are contained in section 2 of this report.

2. Proper design of prototype smoke control systems should consist of (a) design estimate according to physical laws similar to those contained in section 2 of this report and (b) realistic smoke simulation experiments with quantitative measurements such as the SF_6 technique used in this program (c) computer calculations for correlation with experiment and to cover extended weather conditions.

3. The high noise level of large, high velocity pressurization units can be an objectionable feature even though it is designed for safety. A possible solution for this is both optimum design and breakdown of large pressurization units into smaller units distributed vertically along the stairwell.

4. As a result of the added force required to open stairwell doors due to pressurization, it is recommended that a design specification be required to limit the maximum force needed to open pressurized stairwell doors.

9.0 ACKNOWLEDGEMENTS

The computer program used for predicting the performance of the stairwell was developed with help from Dr. Tamami Kusuda of the National Bureau of Standards. The field data collection was supported by a contract from the Department of Housing and Urban Development.

Messrs. James Steel, Richard Zile and Tom Lee of Building Fires and Safety Section, National Bureau of Standards, were most helpful in the data collection.

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Table 1 Experimental Test Configurations

Test No	Simulated Fire	Stairwell Pressurization	Stairwell Doors Open
3a	2nd Floor	"on"	All closed
3b	2nd Floor	"on"	2nd Floor
3e repeat	2nd Floor	"on"	2nd & 11th
4b	2nd Floor	"off"	2nd Floor
5a	9th Floor	"on"	All Closed
5a repeat	9th Floor	"on"	All Closed
5c	9th Floor	"on"	9th & 11th
5g	9th Floor	"on"	2nd, 9th & 11th
7	For description of pressurization shake down test		
8	See Section 6.0, article 4 on Page 18		

Table 2

Test 3a, "Fire on Second Floor", Pressurization "On", all Stairwell Doors Closed

	Corridor				Stairwell			
Floor Level	Dilution	Meter Reading	Concentration ppb	Ratio Normalized by B.R.	Dilution	Meter Reading	Concentration ppb	Ratio Normalized by B.R.
Time 30 min								
2	1:100	20-21	3377.3	1	1:1	10-8	5.2	.001
5	1:1	50-12	56.8	.017		---	---	---
9	1:1	50-13	65.1	.019		---	---	N.C.*
11	1:1	50-17	85.9	.026		---	---	---
Time 40 min								
2	1:100	20-20	3167.1	1	1:1	10-8		.001
5	1:1	20-38	88.5	.028		---	---	---
9	1:1	20-40	99.8	.032		---		N.C.
11	1:1	50-17	85.9	.027		---	---	---
Time 50 min								
2	1:100	20-21	3377.3	1		---	---	---
5	1:1	50-13	65.1	.019		---		N.C.
9	1:1	50-14	74.6	.022		---	---	---
11	1:1	20-46	156.6	.046	1:1	10-16		
Time 60 min								
2	1:100	20-21	3377.3	1	1:1	20-10	13.8	.004
5	1:10	20-13	186.7	.055	1:1	10-18	13.0	.004
9	1:10	20-9	123.0	.036	1:1	10-12	7-9	.002
11	1:10	---		---	1:1	10-18	13.0	.004

* N.C.: No sample collected, break down of sampling procedure
Outdoor temperature: 64°F
Average Indoor Temperature: 73°F

Table 3

Test 3b, "Fire on Second Floor" Pressurization "on", Second Floor Stairwell Door Open

	Corridor				Stairwell			
Floor Level	Dilution	Meter Reading	Concen-tration ppb	Ratio Normalized by B. R.	Dilution	Meter Reading	Concen-tration ppb	Ration Normalized by B.R.
Time 5 min								
2	1:100	20-24	4054.3	1	1:1	5-2	.6	.000
5	1:1	20-14	20.4	.005	1:1	5-4	1.3	.000
9	1:1	20-30	56.8	.014	1:1	5-0	N.D.	N.D.*
11	1;1	20-21	33.8	.008	1:1	5-0	N.D.	N.D.
Time 15 min								
2	1:100	20-29	5378.5	1	1:1	5-1	---	.000
5	1:1	20-13	18.7	.004	1:1	5-3	---	.000
9	1:1	20-42	113.6	.021	1:1	5-8	2.5	.000
11	1:10	20-25	429.8	.080	1:1	5-13	4.5	.001
Time 25 min								
2	1:100	20-36	7892.4	1	1:1	5-11	3.8	.001
5	1:1	20-23	38.2	.005	1:1	5-3	---	.000
9	1:10	20-36	789.2	.100	1:1	5-6	---	.000
11		Lost	---	---	1:1	5-18	56.4	.001

* N.D.: Not detectable
Outdoor temperature: 55°F
Average indoor temperature: 75°F

Table 4

Test 3e repeat, "Fire on Second Floor", Second and Eleventh Floor Stairwell Doors Open

	Corridor				Stairwell			
Floor Level	Dilution	Meter Reading	Concen-tration ppb	Ratio Normalized by B.R.	Dilution	Meter Reading	Concen-tration ppb	Ratio Normalized by B.R.
Time 5 min								
2	1:10	20-20	316.7*	1	1:1	2-0		N.D.
5	1:1	20-8	10.8	.034	1:1	1-0		"
9	1:1	10-12	7.9	.025	1:1	2-0		"
11	1:1	2-9	1.3	.004	1:1	5-0		"
Time 15 min								
2	1:10	20-19	296.4	1	1:1	1-0		"
5	1:1	20-9	12.3	.042	1:1	1-0		"
9	1:1	20-8	10.8	.036	1:1	1-0		"
11	1:1	20-9	12.3	.042	1:1	1-0		"
Time 25 min								
2	1:10	20-22	359.5	1	1:1	1-0		"
5	1:1	20-10	13.8	.039	1:1	1-0		"
9	1:1	20-12	17.0	.047	1:1	1-0		"
11	1:1	20-6	7.9	.022	1:1	1-0		"

N.D.: Not detectable
Outdoor temperature: 65°F
Indoor temperature: 72°F

*Ball type Flow meter setting: 4

Table 5

Test 4b, "Fire on Second Floor" Stairwell Pressurization "Off", Second Floor Stairwell Door Open

	Corridor				Stairwell			
Floor Level	Dilution	Meter Reading	Concentration ppb	Ratio Normalized by B.R.	Dilution	Meter Reading	Concentration ppb	Ratio Normalized by B.R.
Time 5 min								
2	1:100	20-40	9978.15	1	1:1	Lost	---	---
5	1:1	10-36	27.7	.027	1:1	50-19	185.7	.185
9	1:1	20-14	20.4	.020	1:1	5-12	3.8	.004
11	1:1	50-19	185.7	.185	1:1	5-18	5.8	.006
Time 15 min								
2	1:100	20-26	4550	1	1:100	20-19	2963.8	.651
5	1:1	50-19	185.7	.041	1:100	20-20	3167.1	.696
9	1:1	20-36	78.9	.017	1:10	20-13	186.7	.041
11	1:10	20-47	1744.3	.38	1:10	20-14	203.7	.045
Time 25 min								
2	1:100	20-26	4550	1	1:100	20-18	2767.0	.608
5	1:10	20-24	4054	.089	1:100	20-20	3167.1	.696
9	1:10	20-15	221.1	.049	---	Lost	---	---
11	1:10	20-46	1566.0	.344	1:10	10-32	239.1	.053

Outdoor temperature: 59°F
Indoor temperature: 74°F

Table 6

Test 5a, "Fire on Ninth Floor" all Stairwell Doors Closed, Pressurization "On"

	Corridor				Stairwell			
Floor Level	Dilution	Meter Reading	Concen-tration ppb	Ratio Normalized by B.R.	Dilution	Meter Reading	Concen-tration ppb	Ratio Normalized by B.R.
Time 5 min								
2	1:1	5-2	.6	.002	1:1	1-0		N.D.
5	1:1	10-22	15.4	.049	1:1	1-0		"
9	1:10	20-20	316.7*	1	1:1	1-0		"
11	1:1	5-28	9.4	.030	1:1	1-0		"
Time 15 min								
2	1:1	5-2	.6	.001	1:1	1-0		"
5	1:1	10-22	15.4	.036	1:1	1-0		"
9	1:10	20-25	429.8	1	1:1	1-0		"
11	1:1	20-31	60.0	.140	1:1	1-0		"
Time 25 min								
2	1:1	5-4	1.3	.003	1:1	1-0		"
5	1:1	20-14	20.4	.045	1:1	1-0		"
9	1:10	20-26	455.1	1	1:1	1-22		"
11	1.1	20-42	113.6	.25	1:1	1-0		"

N.D.: Not detectable
Outdoor temperature: 62°F
Indoor temperature: 75°F

*Ball type flow meter setting: 4

Table 7

Test 5a repeat, "Fire on Ninth Floor", all Stairwell Doors Closed, Pressurization "On"

	Corridor				Stairwell			
Floor Level	Dilution	Meter Reading	Concentration ppb	Ratio Normalized by B.R.	Dilution	Meter Reading	Concentration ppb	Ratio Normalized to B.R.
Time 5 min								
2	1:1	2-2	.3	.001	1:1	1-0		N.D.
5	.1	10-21	14.6	.057	1:1	1-0		"
9	1:10	20-17	257.6*	1	1:1	1-0		"
11	1:1	5-16	5.2	.02	1:1	1-0		"
Time 15 min								
2	1:1	1-6	.4	.001	1:1	1-0		"
5	1:1	10-26	18.7	.041	1:1	1-0		"
9	1:10	20-26	455.1	1	1:1	1-0		"
11	1:1	20-22	35.9	.079	1:1	1-0		"
Time 25 min								
2	1:1	1-7	.4	.001	1:1	1-0		"
5	1:1	10-13	8.6	.021	1:1	1-0		"
9	1:10	20-24	405.4	1	1:1	1-0		"
11	1:1	20-34	70.6	.174	1:1	1-0		"

* Ball type flow meter setting: 4
Outdoor temperature: 59°F
Indoor temperature: 75°F

Table 8

Test 5c, "Fire on Ninth Floor", Pressurization "On", Ninth and Eleventh Floor Stairwell Doors Open

	Corridor				Stairwell			
Floor Level	Dilution	Meter Reading	Concentration ppb	Ratio Normalized by B.R.	Dilution	Meter Reading	Concentration ppb	Ratio Normalized by B.R.
Time 5 min								
2	1:1	5-3	.9	---	1:1	1-0	N.D.	N.D.
5	1:1	10-25	17.8	---	1:1	1-25	1.6	---
9	1:1	Lost	---	---	1:1	10-10	6.5	---
11	1:1	5-7	2.2	---	1:1	5-0	N.D.	N.D.
Time 15 min								
2	1:1	5-7	2.2	---	1:1	1-0	N.D.	N.D.
5	1:1	10-42	33.8	---	1:1	1-0	"	"
9	1:10	10-18	123.0*	---	1:1	1-0	"	"
11	1:1	2-8	1.0	---	1:1	1-9	.6	---
Time 25 min								
2	1:1	2-28	3.31	.006	1:1	1-0	N.D.	N.D.
5	1:1	20-44	131.5	.244	1:1	1-0	"	"
9	1:10	20-29	537.9	1	1:1	2-8	1.0	.002
11	1:1	1-0	N.D.	N.D.	1:1	1-0	N.D.	N.D.

N.D.: Not detectable
Outdoor temperature: 65°F
Indoor temperature: 75°F
*Ball type flow meter setting: 4

Table 9

Test 5g, "Fire on Ninth Floor", Stairwell Pressurization "On", Second, Ninth and Eleventh Floor Stairwell Doors Open

	Corridor				Stairwell			
Floor Level	Dilution	Meter Reading	Concen-tration ppb	Ratio Normalized by B.R.	Dilution	Meter Reading	Concen-tration ppb	Ratio Normalized by B.R.
Time 5 min								
2	1:1	5-5	1.6	.001	1:1	2-5	.6	.001
5	1:1	50-10	43.0	.033	1:1	2-7	.9	.001
9	1:10	20-44	1314.5*	1	1:1	2-5	.6	.001
11	1:1	5-6	1.9	.001	1:1	2-11	1.4	.001
Time 15 min								
2	1:1	5-8	2.5	.002	1:1	2-9	1.2	.001
5	1:1	50-9	37.1	.035	1:1	2-5	.6	.001
9	1:10	20-41	1063.1	1	1:1	2-7	.9	.001
11	1:1	2-6	.6	.001	1:1	2-11	1.4	.001
Time 25 min								
2	1:1	5-10	3.2	.002	1:1	2-12	1.5	.001
5	1:1	20-38	88.5	.062	1:1	2-8	1.0	.001
9	1:10	20-45	1427.6	1	1:1	2-10	1.3	.001
11	1:1	2-11	1.4	.001	1:1	2-8	1.0	.001

Outdoor temperature: 60°F
Indoor temperature: 74°F
*Ball type flow meter setting: 6

Table 10

Test 7, "Fire on Second Floor", Pressurized Stairwell "Shake Down", Stairwell Doors Being Opened at 2 Minute Intervals, Beginning Eleventh Floor at 5 Minute

	Stairwell			
Floor Level	Dilution	Meter Reading	Concentration ppb	Ratio Normalized by B.R.
2	1:100	10-12	792.6	.221
3	1:10	20-16	239.1	.067
4	1:1	20-34	70.6	.020
5	1:1	20-44	131.5	.037
6	1:1	10-14	9.4	.003
7	1:1	10-18	12.3	.003
8	1:1	10-10	6.5	.002
9	1:1	5-10	3.2	.001
10	1:1	5-10	3.2	.001
11	1:1	5-10	3.2	.001
B.R.	1:100	10-44	3594.9	

Outdoor temperature: 58°F
Average indoor temperature: 72°F

Table 11

Test 8, "Fire on Ninth Floor" Pressurized Stairwell "Shake Down", Stairwell Doors Being Opened at 2 Minute Intervals, Beginning Eleventh Floor at 5 Minute

Stairwell				
Floor Level	Dilution	Meter Reading	Concentration ppb	Ratio Normalized by B.R.
2	1:1	10-12	7.9	.002
3	1:10	10-12	79.3	.022
4	1:1	50-18	142.8	.040
5	1:10	5-20	65.3	.018
6	1:1	50-16	99.8	.028
7	1:1	20-40	99.8	.028
8	1:1	20-23	38.2	.011
9	1:10	10-10	65.3	.018
10	1:1	5-10	1.4	.000
11	1:1	5-11	1.4	.000
B.R.	1:100	20-22	3595	1

Outdoor temperature: 59°F
Average indoor temperature: 74°F

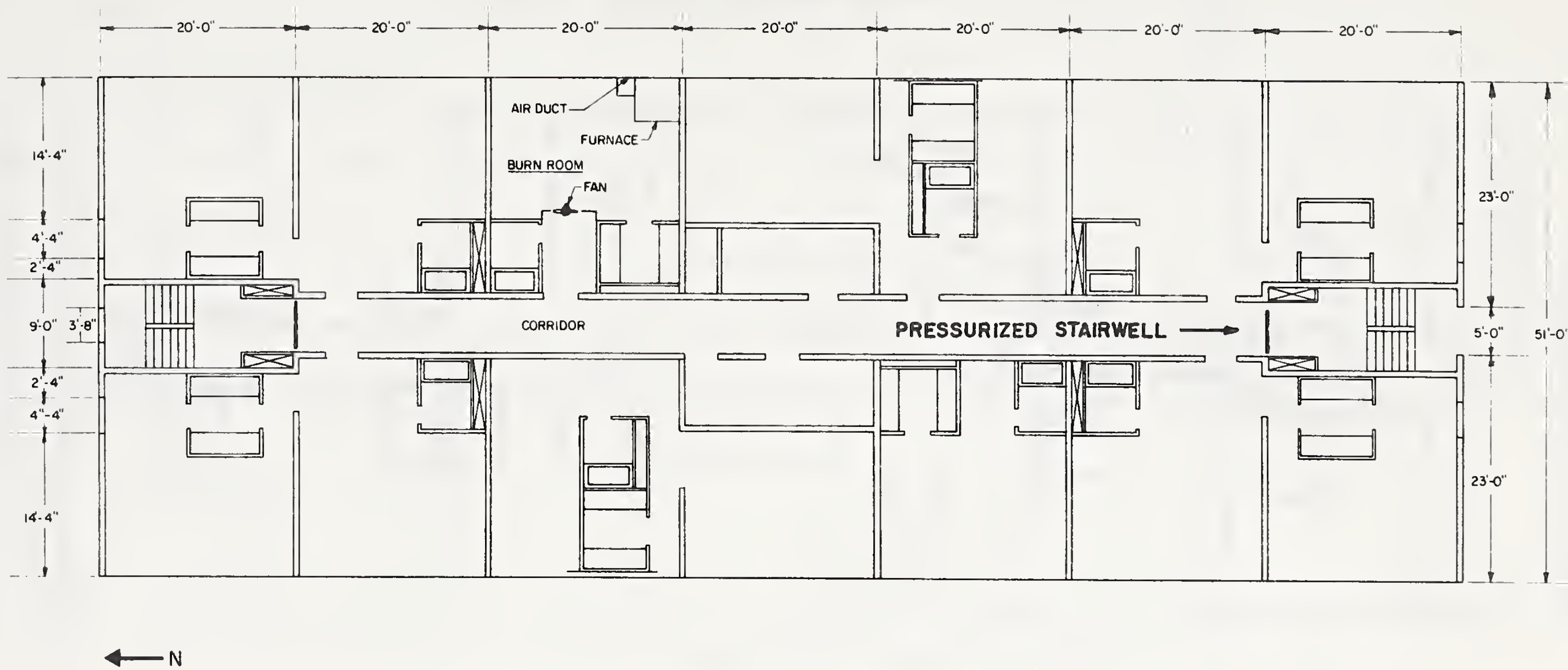


FIG. 1 SECOND FLOOR PLAN WITH 'BURN ROOM'

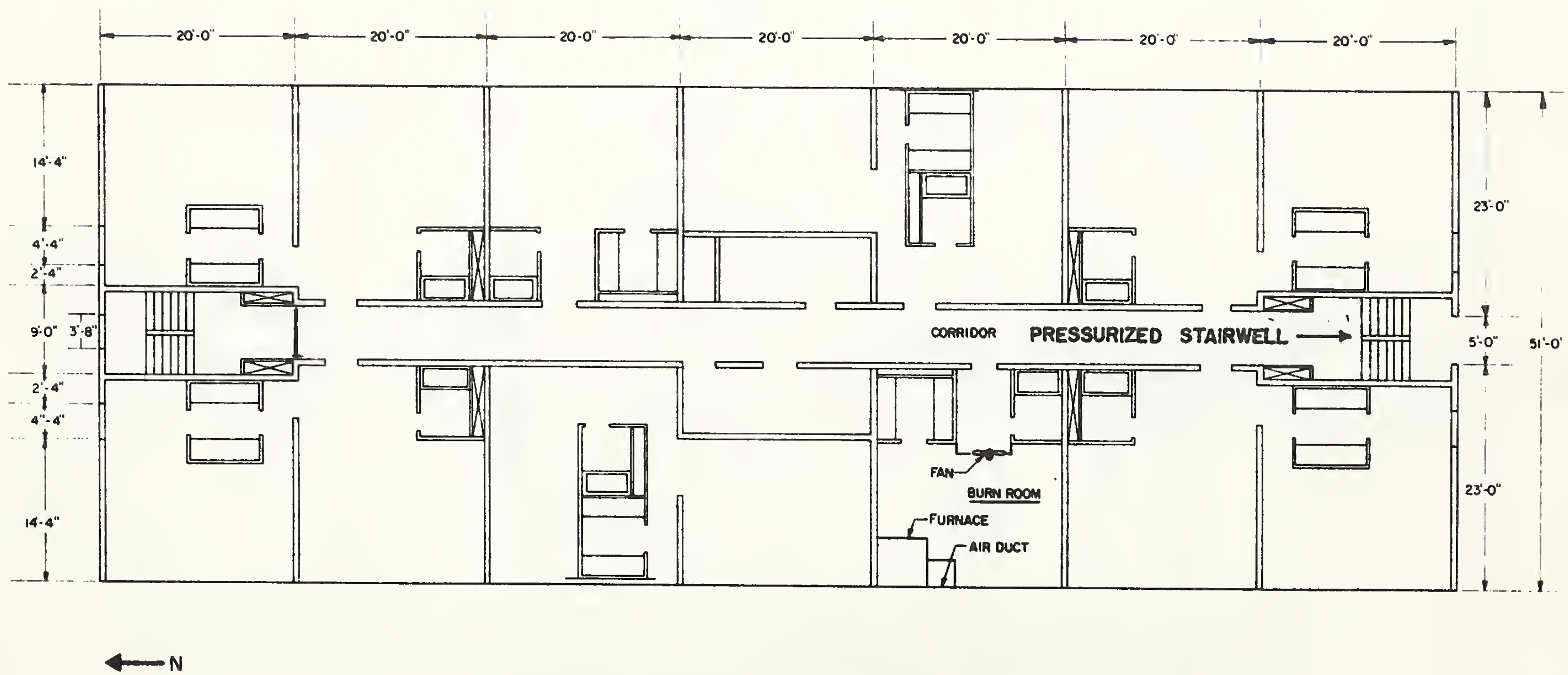


FIG. 2 NINTH FLOOR PLAN WITH 'BURN ROOM'

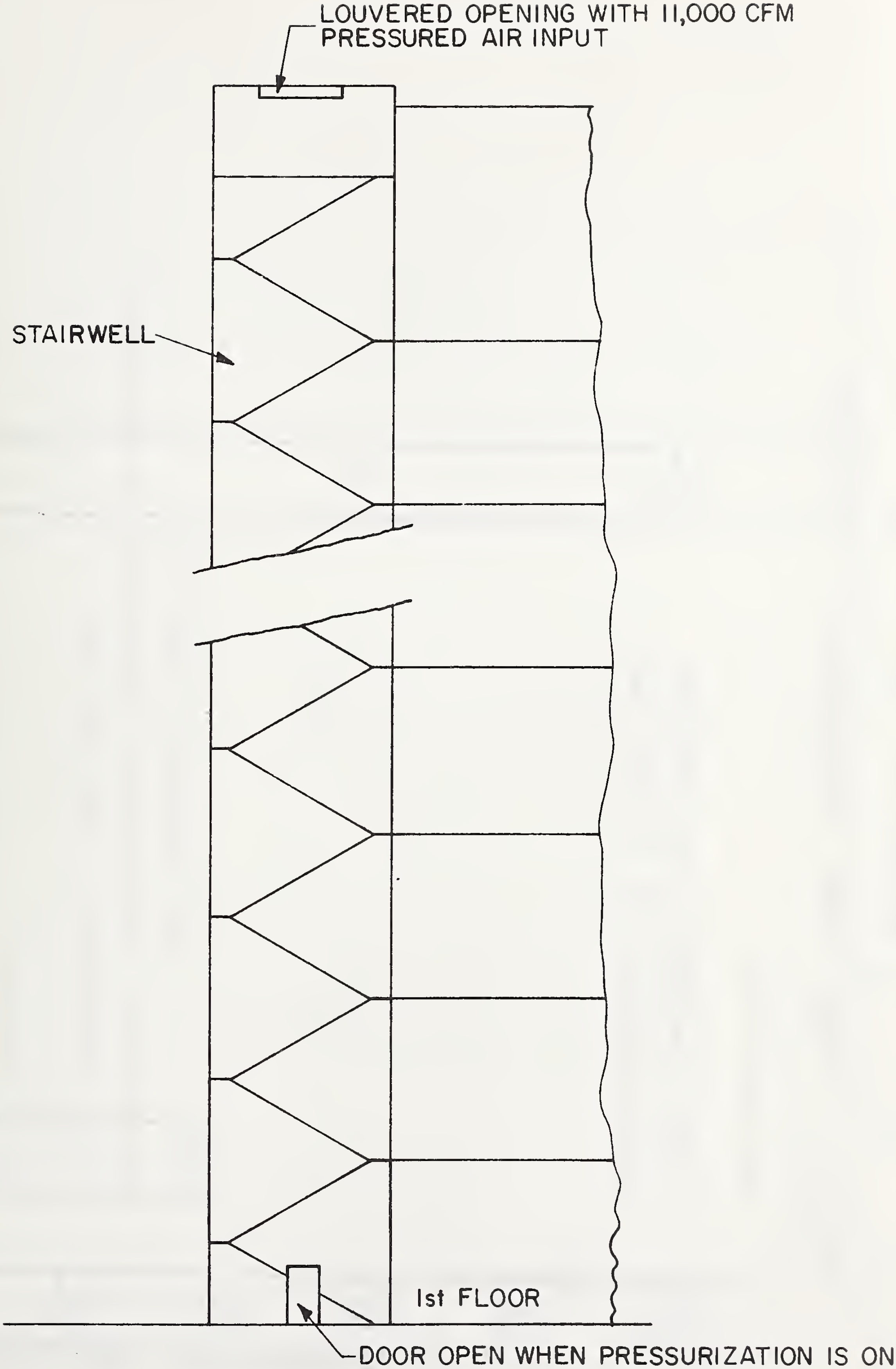
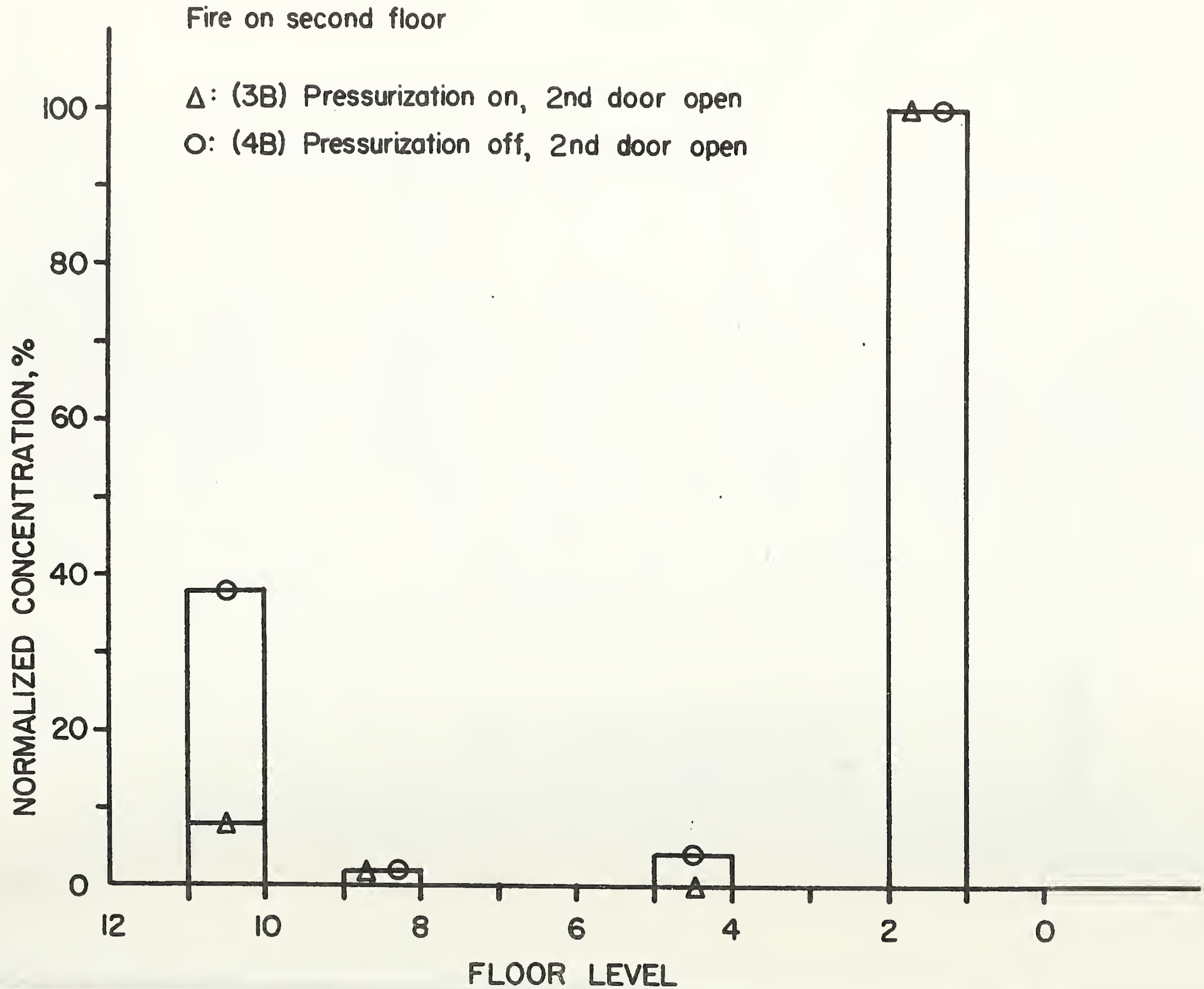


FIG. 3, PRESSURIZATION FLOW SUPPLY AND VENT

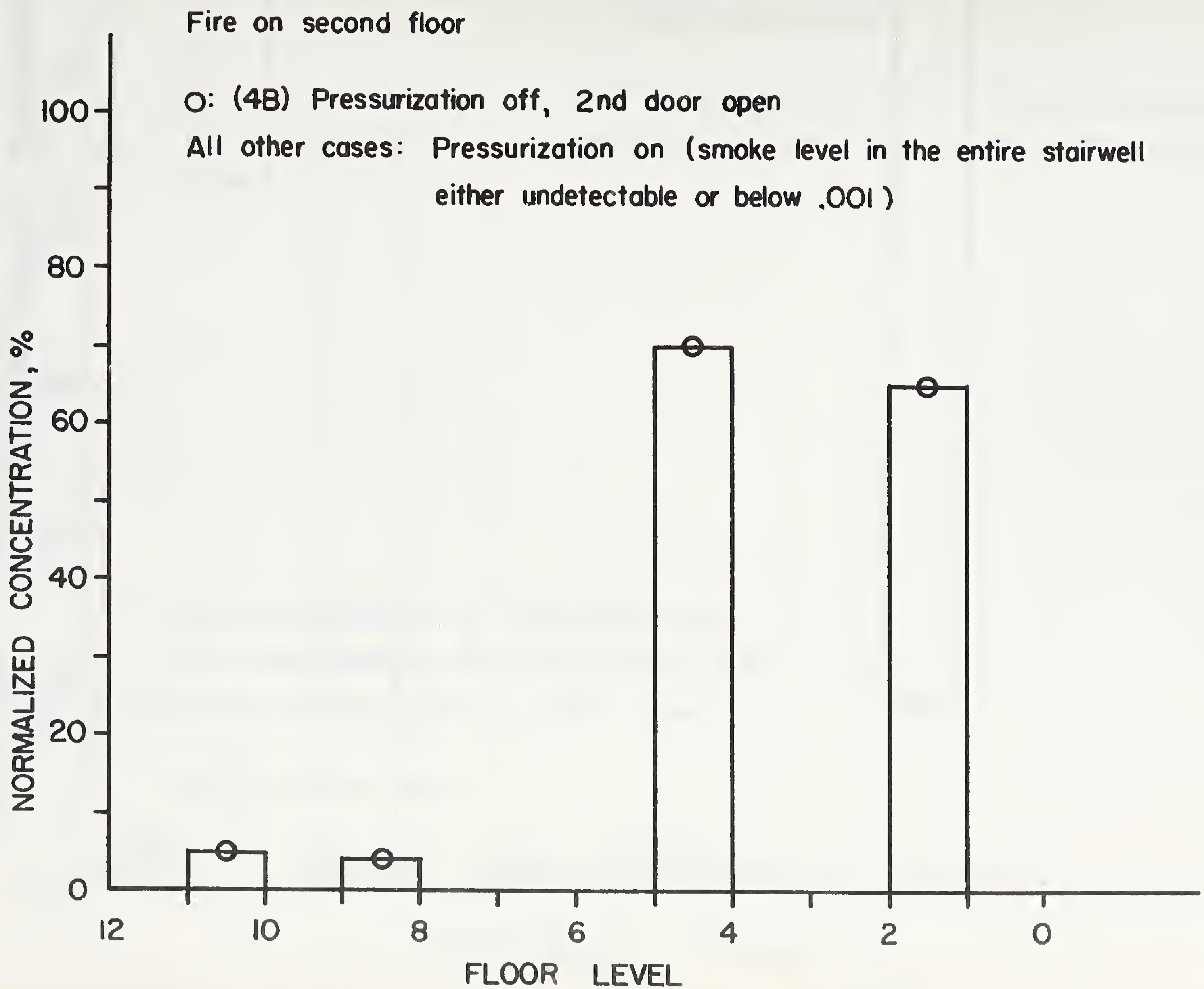
SIMULATED SMOKE TEST

Fig. 4 Corridor Smoke Comparisons at 15 minutes



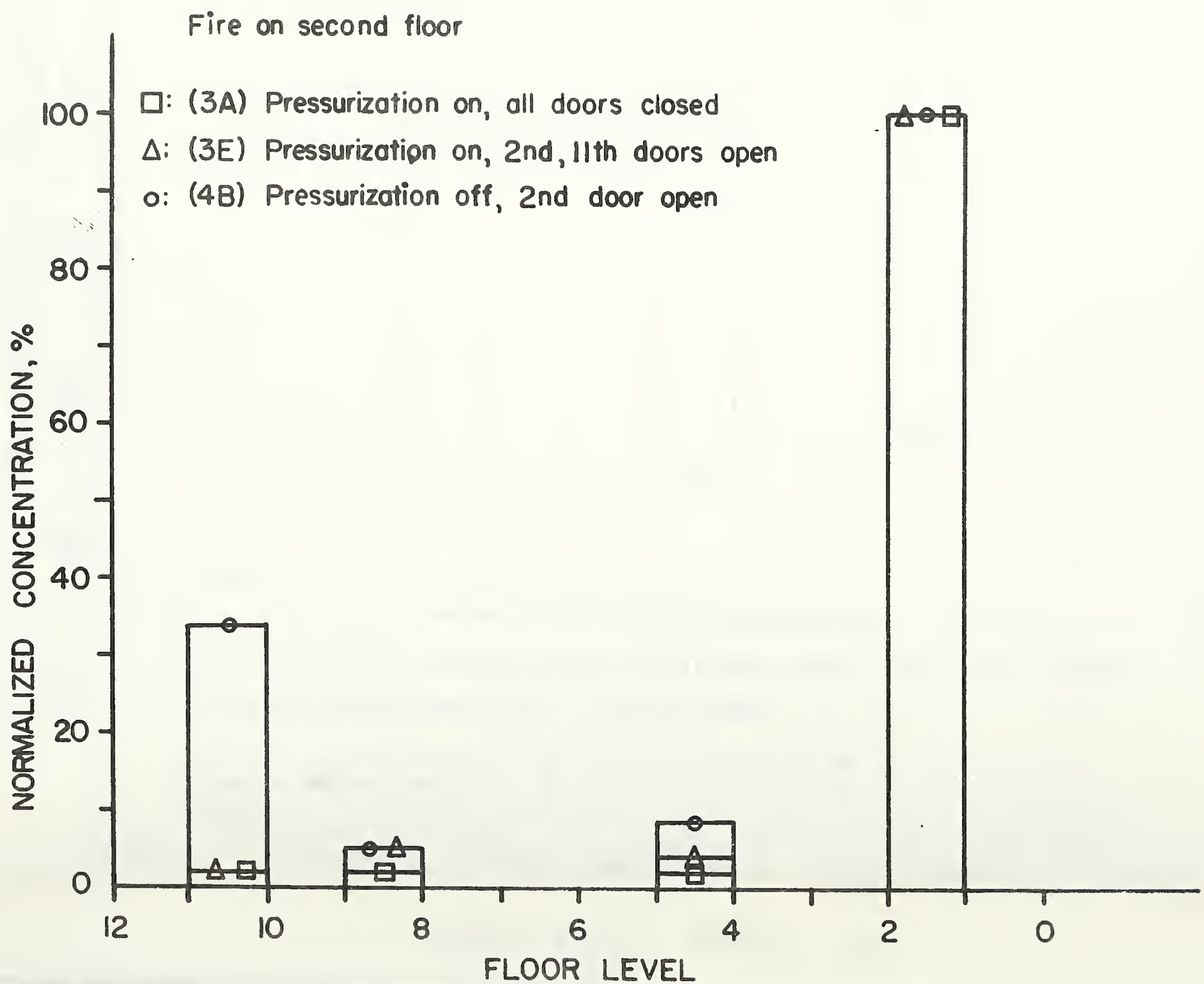
SIMULATED SMOKE TEST

Fig. 5 Stairwell Smoke Comparisons at 15 minutes



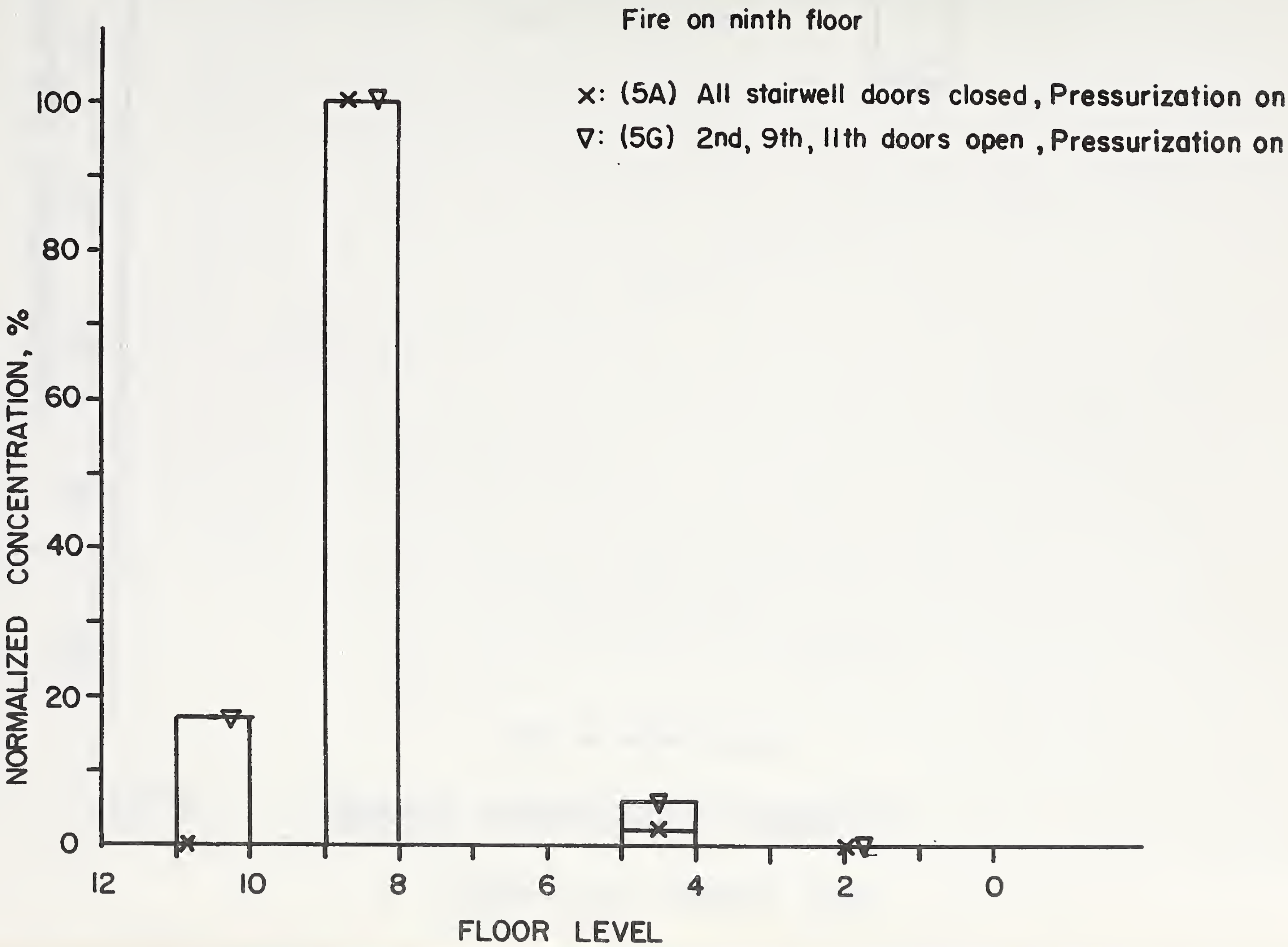
SIMULATED SMOKE TEST

Fig. 6 Corridor Smoke Comparisons at 25 minutes



SIMULATED SMOKE TEST

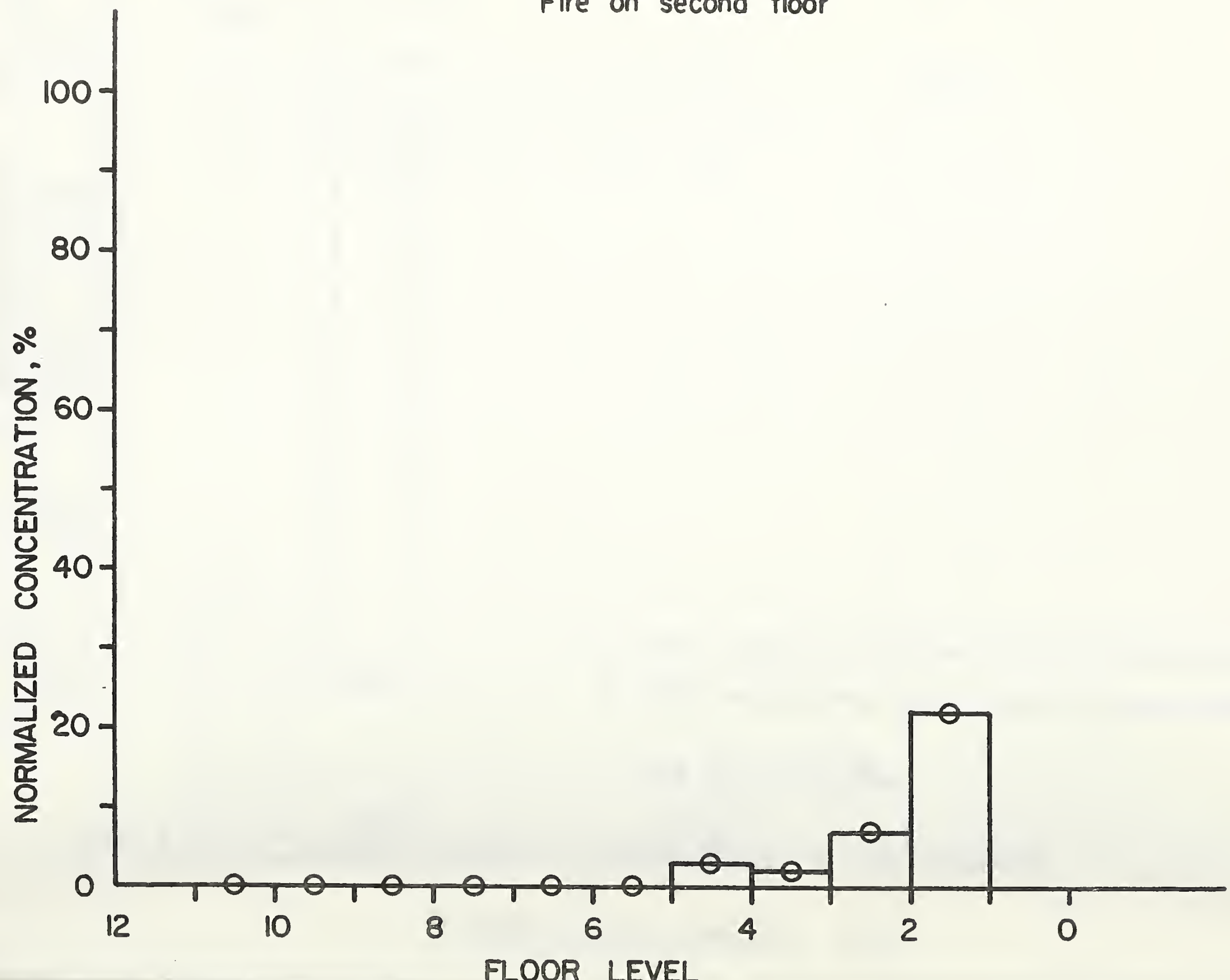
Fig. 7 Corridor Smoke Comparisons at 25 minutes



SIMULATED SMOKE TEST

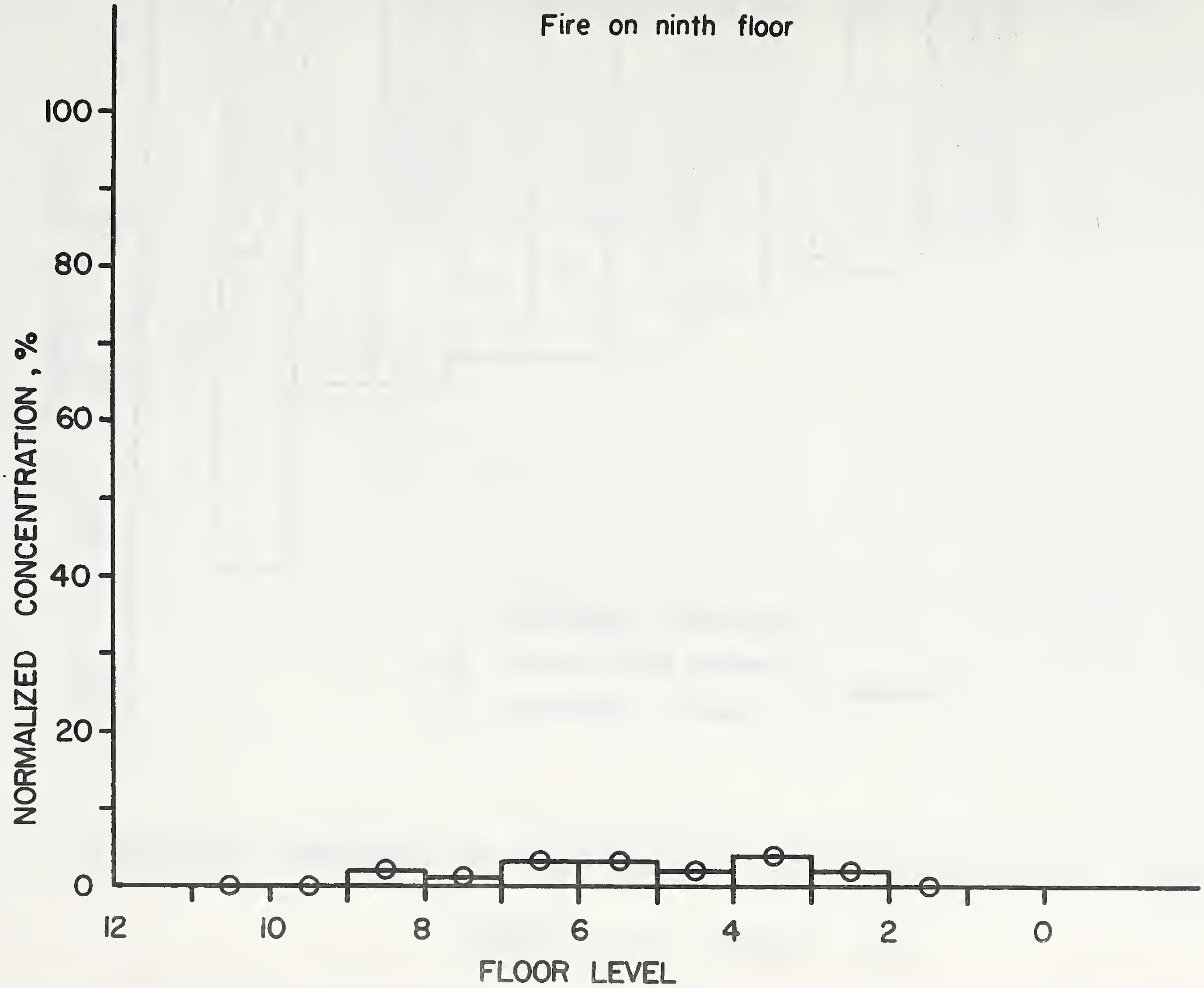
Fig. 8 Stairwell Pressurization Shakedown

Fire on second floor



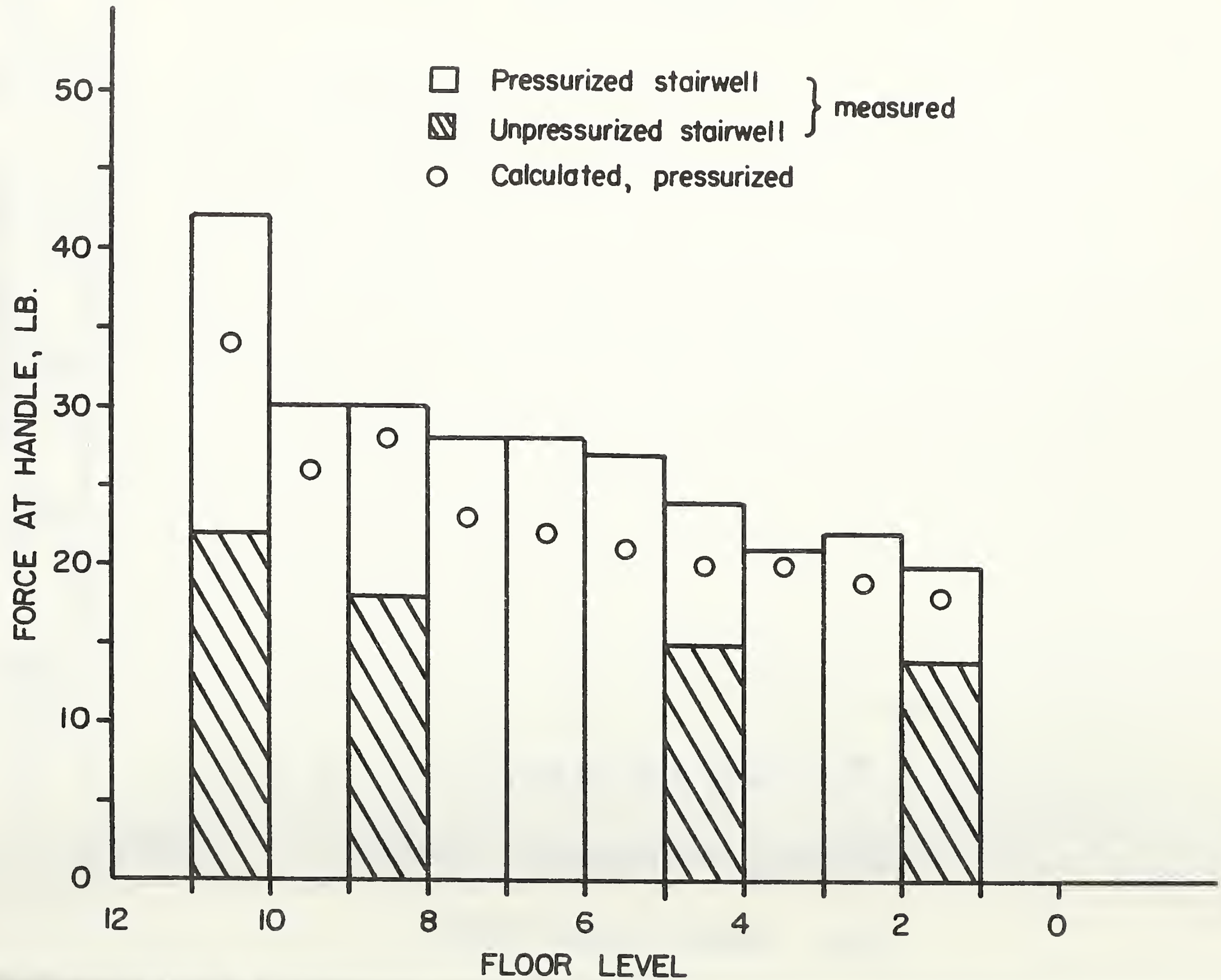
SIMULATED SMOKE TEST

Fig. 9 Stairwell Pressurization Shakedown



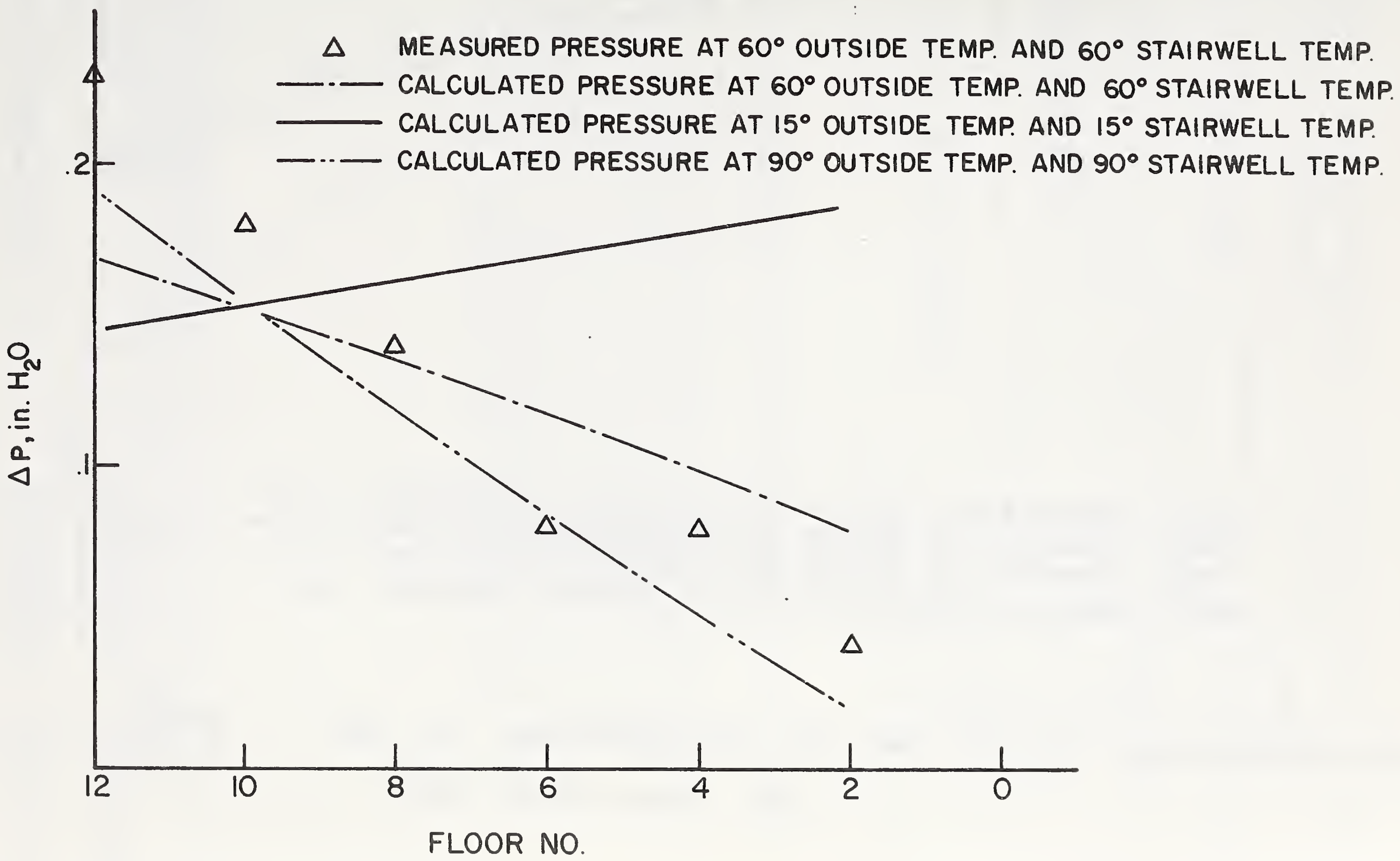
SIMULATED SMOKE TEST

Fig.10 Measured Force Required to Open Stairwell Doors (Initial Maximum)



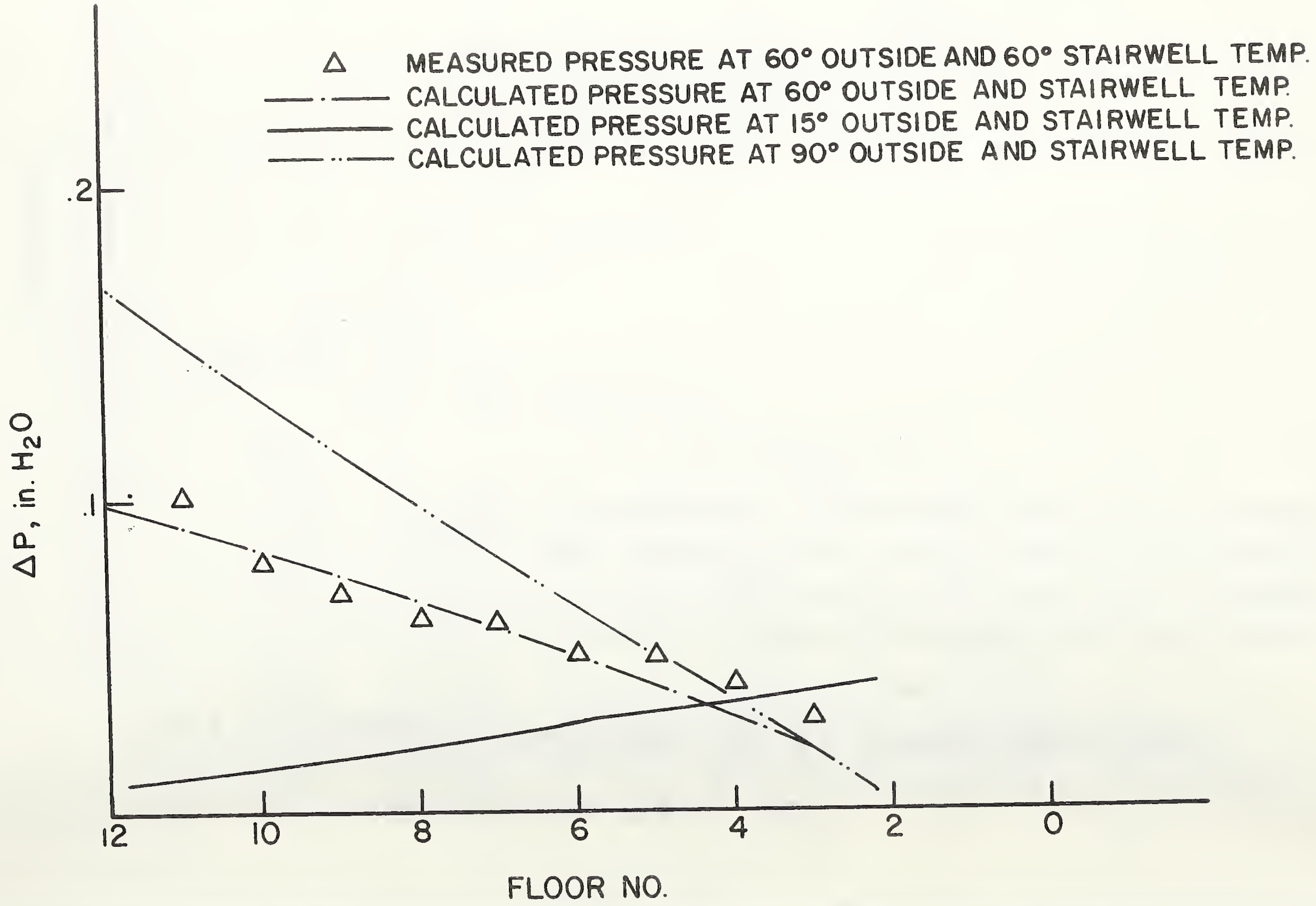
SIMULATED SMOKE TEST

Fig. 11 Case 3A, Pressurization On, All Stairwell Doors Closed



SIMULATED SMOKE TEST

Fig. 12 Case 3E, Pressurization On, 2nd and 11th Floor Stairwell Doors Open



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U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBSIR 73-277	2. Gov't Accession No.	3. Recipient's Accession No.
4. TITLE AND SUBTITLE Evaluation of a Pressurized Stairwell Smoke Control System for a 12 Story Apartment Building			5. Publication Date June 1973 6. Performing Organization Code
7. AUTHOR(S) Francis C. W. Fung			8. Performing Organization NBSIR 73-277
9. PERFORMING ORGANIZATION NAME AND ADDRESS NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, D.C. 20234			10. Project/Task/Work Unit No. 4608412 11. Contract/Grant No. IAA-H-37-72
12. Sponsoring Organization Name and Address Office for Policy Development and Research Department of Housing and Urban Development Washington, D.C. 20410			13. Type of Report & Period Covered Final 14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

An NBS study to evaluate the effectiveness of a pressurized stairwell smoke control system in a high rise apartment building is summarized and discussed in the light of experimental results, analysis, and computer prediction. A quantitative experimental technique of smoke simulation and smoke movement measurement is described, supplemented by basic physical laws necessary for correlation with small fires, and illustrated by the results of an actual field experiment. Experiments were conducted in a 12 story apartment building constructed on the Operation BREAKTHROUGH prototype site in St. Louis, Missouri. The experimental results are then further extended to a wider range of ambient weather conditions by way of computer prediction calculations. General conclusions and relevant recommendations as a result of the study are also presented.

17. KEY WORDS (Alphabetical order, separated by semicolons)
Analysis; basic correlation formulas; computer calculations; high-rise building fire; Operation BREAKTHROUGH; pressurized stairwell; quantitative experiment; smoke control; smoke simulation

18. AVAILABILITY STATEMENT	19. SECURITY CLASS (THIS REPORT)	21. NO. OF PAGES
[XX] UNLIMITED.	UNCLASSIFIED	
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